



Urbanization effects on heat waves in Fujian Province, Southeast China

Lijie Lin^a, Erjia Ge^b, Xiaoping Liu^c, Weilin Liao^c, Ming Luo^{c,d,*}

^a Department of Geography and Resource Management, The Chinese University of Hong Kong, Hong Kong, China

^b Dalla Lana School of Public Health, University of Toronto, Toronto, ON, Canada

^c School of Geography and Planning, Sun Yat-sen University, Guangzhou 510275, China

^d Institute of Environment, Energy and Sustainability, The Chinese University of Hong Kong, Hong Kong, China

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ABSTRACT

Heat waves (HWs) exert increasingly profound effects on public health and ecosystems under global warming and regional urbanization. This study examines the changes in the frequency, duration, magnitude, and timing of HWs in Fujian, Southeast China during 1971–2014 and quantifies the possible effects of urbanization using a dynamical classification scheme for urban and rural stations. Considering that some rural stations could have been converted into urban types during the urbanization process, this scheme dynamically classifies urban and rural stations based on time-varying land use/cover maps in different subperiods, thus giving a better estimation of urbanization effects.

Our results show that HWs in Fujian are commencing earlier and ending later, and becoming more frequent, more intense, longer lasting. Particularly, severe (i.e., stronger and longer-lived) HW events have even stronger intensifying trends than regular ones. Moreover, we notice that the intensifying HW activities are especially prominent in densely populated and highly urbanized areas of Fujian. It is estimated that urbanization contributes to approximately half of the increasing HWs. Urbanization induces an additional increase of 0.15 events (3.78 days) per decade to HW frequency (participating days), accounting for 40.3% (57.5%) of the total trend. Meanwhile, 50.4% (60.8%) of the prolonging trend in the average (longest) duration and 27.0% (65.0%) of the intensifying trend in the average (strongest) magnitude are attributable to urbanization, i.e., 1.71 (1.19) days per decade and 0.18 (0.08) °C per decade, respectively. Moreover, urbanization induces further advancing (delaying) trend of 1.37 (1.39) days per decade for the onset (ending) date of HW in the calendar year. The findings presented here uncover the multi-faceted behaviors of HW and advance the existing research by providing a broader picture of this extreme event. It is also recommended to consider these various HW aspects in the research of climate change and extreme climate events.

1. Introduction

Heat wave (HW) is an extreme event that seriously threatens human and natural systems (Easterling et al., 2000b; Meehl and Tebaldi, 2004). With global warming, the HW activities in many parts of the world have been intensifying during the past decades and are projected to increase and pose increasingly severe threats to society in the future (Kunkel et al., 2010; IPCC, 2012, 2013; Cowan et al., 2014; Luo and Lau, 2018). The study on the long-term change of HWs is significant to detect the attribution of global and regional climate change and to assess the impacts of climate change on human society and natural systems.

China has been severely suffering from HWs and extremely high temperatures (Ding et al., 2010; Lu and Chen, 2016; Luo and Lau, 2017). 5758 HW-related illness cases have been reported during the summer of 2013 in China (Gu et al., 2015). Many studies have

documented the warming trends in China during last decades (Ren et al., 2005; Liu et al., 2006; Zhang et al., 2011; Sun et al., 2016a; Wen et al., 2017; You et al., 2017). For instance, Ren et al. (2005) suggested that the mean temperature in China has increased by 0.22 °C decade⁻¹ during 1951–2002. Cool nights (days) decreased by 28.23 (23.26) days decade⁻¹ and warm nights (days) increased by 8.16 (5.22) days decade⁻¹ (Zhou and Ren, 2011). These intensifying trends are particularly prominent in highly urbanized areas such as the North China (Ren et al., 2008; Wang et al., 2013; Zhang et al., 2015), the Yangtze River Delta (Gu et al., 2011; Guan et al., 2015), and the Pearl River Delta (Fischer et al., 2012; Luo and Lau, 2017). Thus, urbanization has been considered as an important factor in China's warming.

Ren and Zhou (2014) estimated that the urbanization effects on the annual mean of daily minimum ($T_{\min}$) and maximum temperature ($T_{\max}$) in China are 0.07 and 0.023 °C decade⁻¹, respectively. Sun et al.

* Corresponding author at: School of Geography and Planning, Sun Yat-Sen University, Guangzhou 510275, China.
E-mail address: luo.ming@hotmail.com (M. Luo).

(2016b) further estimated that urbanization accounts for around one-third of the total warming trend in eastern China during 1961–2013. It has also been found that around half of the increasing HW frequency in southern China is induced by urbanization (Luo and Lau, 2017). Specifically, urbanization contributes about 44% and 35% to the total warming in the metropolis and large city areas, respectively (Fischer et al., 2012). For instance, a simulation study showed that urbanization induces 0.74 °C warming in Hangzhou of eastern China (Chen et al., 2014).

These previous studies mainly focused on the effects of urbanization on daily temperatures and daily extremes but neglect the effects on HW, a consecutive (e.g., three or more days) extremely high-temperature event (Robinson, 2001; Radinović and Ćurić, 2012; Perkins and Alexander, 2013; Zuo et al., 2015; You et al., 2017). The urbanization effects on HW activity have yet to be fully understood. Moreover, existing studies examined the urbanization effect on local climate at national or subregional scales (e.g., the Yangtze River Delta), and no systematic study has been conducted on the impacts of urbanization at the provincial scale. Therefore, this study selects the case of Fujian Province in southeast China to examine the trend of HW and the influence of urbanization on HW activity, by considering the local specific context. Such an investigation is essential for provincial government and related departments to adapt and mitigate climate change.

Fujian is located a joint region connecting the Yangtze River Delta and the Pearl River Delta, the most populated and developed regions in China. Though Fujian's urbanization level is not high as these two regions, it has been experiencing fast urbanization during the past decades (Zhu, 2000; Shen and Lin, 2017). As one of the most densely urbanized and populated areas in China, Fujian had a population of 36.9 million in 2010 (Fujian Office for Population Census, 2013). The urbanization level of Fujian was 20% in 1980, and it kept sustained growth in the reform era and exceeded 57% in 2010 (Shen and Lin, 2017).

It remains unknown how HW in Fujian changed during the last decades and whether, or to what degree, urbanization process in Fujian contributed to the long-term trends of the HW activity. Therefore, the primary purpose of this study includes a) to examine the long-term changes of various aspects of Fujian's HW including frequency, duration, magnitude, and timing, and b) to quantify the effect and contribution of urbanization to these changes.

2. Data and methodology

2.1. Study region

Fujian Province is located in the southeast coastal area of China (Fig. 1a), with a total area of 124,000 km². Fujian is characterized by a typical tropical climate, with hot summer and mild winter (Fig. 3). Mean $T_{\min}$ in peak summer (i.e., June–September) is higher than 20 °C (Fig. 3), and high temperatures and HWs regularly occur in this season. The densest population density appears in the southeastern coastal area (Fig. 2a). As shown in Fig. 2b, there is also a clear contrast between coastal and inland areas in terms of development and urbanization (Zhu, 2000; Shen and Lin, 2017). Such uneven spatial variation of urbanization level may induce different secular trend of summer climate and extremes, as discussed in our following analyses.

2.2. Data

Daily observations of $T_{\min}$ over the period of 1971–2014 at 65 state-level meteorological stations in Fujian Province are collected from the China Meteorological Data Service Center at <http://data.cma.cn>. Fig. 1b presents a map showing the locations of these stations. Excluded stations comprise those with missing observations for more than three days in any summer season (i.e., June–September) of 1971–2014.

Urbanization is expressed as the urban built-up area fraction (BAF) derived from the land use/cover maps (Liu et al., 2014, 2017). The land use/cover maps of China are available at eight episodes, i.e., 1980, 1990, 1995, 2000, 2005, 2008, 2010, and 2013. These maps were generated through visual interpretations of the Landsat TM/ETM+ images with a spatial resolution of 30 m (Liu et al., 2014), as provided by the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (<http://www.resdc.cn>).

2.3. Definition of HW

HW can be defined by either daily $T_{\max}$ or $T_{\min}$ series (Radinović and Ćurić, 2012; Perkins and Alexander, 2013; You et al., 2017). Consecutive hot days with or without limited nighttime relief can profoundly influence the rates of excess mortality and morbidity (Karl and Knight, 1997; Meehl and Tebaldi, 2004; Hansen et al., 2008). Therefore, we select daily $T_{\min}$ to define HW events in this study. For the selected variable, HW can be defined based on either absolute or relative threshold [the comparisons between different HW definitions can be referred to Robinson, 2001, Radinović and Ćurić, 2012, Perkins and Alexander, 2013, and You et al., 2017]. In this study, we follow Lau

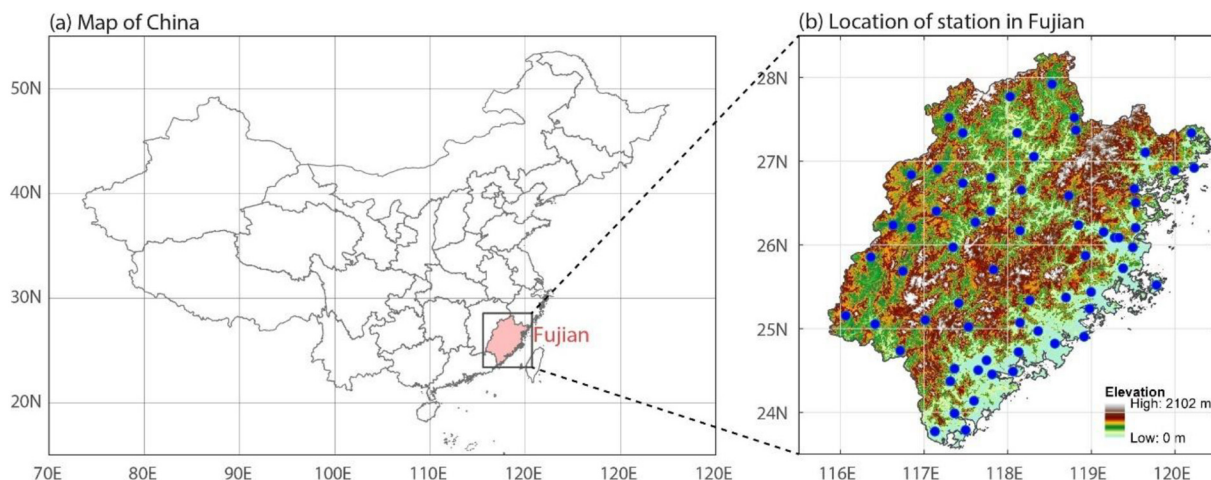


Fig. 1. Map of Fujian Province, Southeast China. Dots indicate the locations of weather stations. The pink shading in (a) denotes Fujian Province. Shading in (b) denotes elevation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

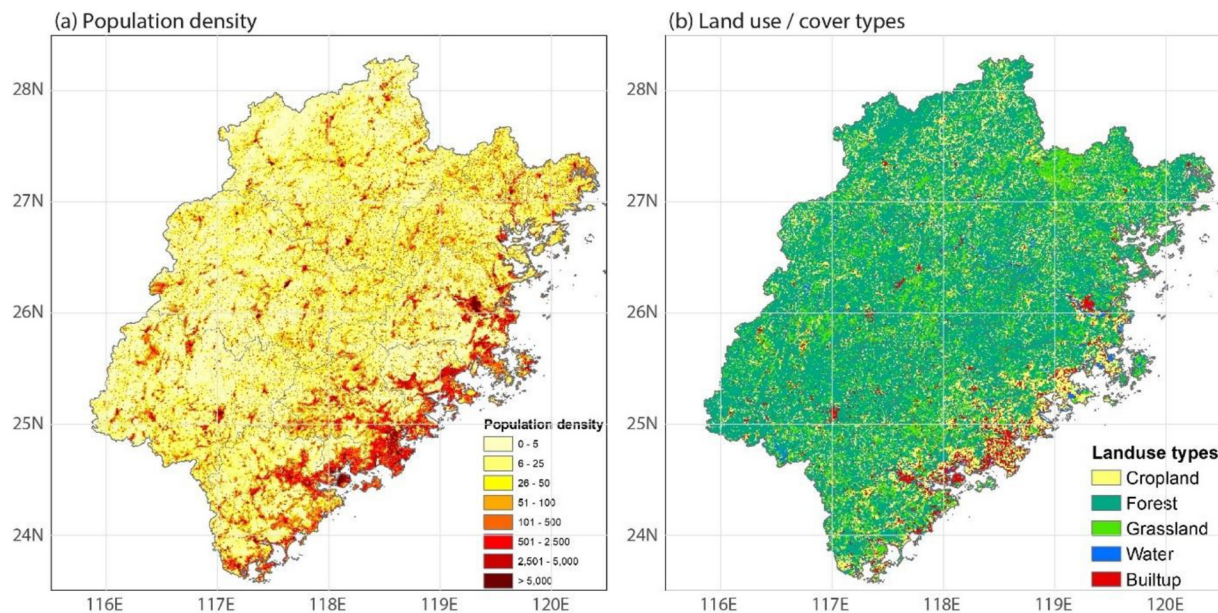


Fig. 2. Population density (left) and land use/cover types (right) in Fujian, 2013. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

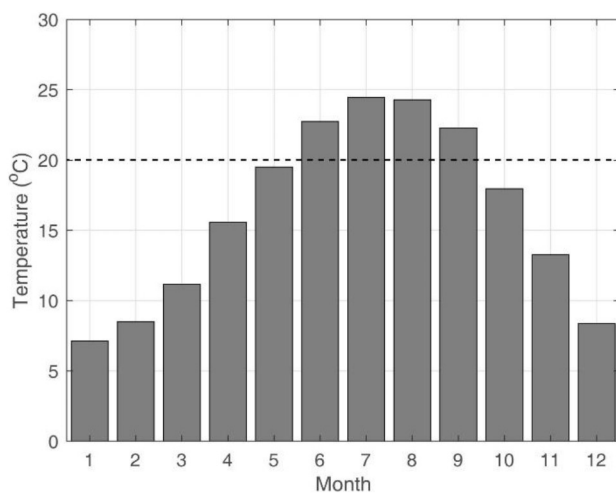


Fig. 3. The climatological mean of the monthly evolution of regional mean $T_{\min}$ in Fujian from 1971 to 2014. Dashed horizontal line denotes 20 °C.

and Nath (2014) and note the 90th and 75th percentile values (hereafter referred to as T1 and T2, respectively) of the population of daily $T_{\min}$. An HW event in a region (at a station) is then defined when: (a) the regional mean of $T_{\min}$ (station- $T_{\min}$) is higher than T1 for three or more consecutive days, (b) the event-averaged value of $T_{\min}$ is higher than T1, and (c) $T_{\min}$ is higher than T2 throughout the event.

To examine the secular trends of various aspects of HW activity, we focus on the HW measures including (Table 1): the yearly number of HW events (HWN), yearly sum of participating HW days (HWF), length of the longest yearly event (HWD), hottest day of the hottest yearly event (i.e., amplitude, HWA), average length of all yearly events (HWL), average magnitude of all yearly events (HWM), onset date of the first event of the year (HWO), and ending date of the last event of the year (HWE). These indicators have also been used to study the HW characteristic in other regions such as South China and the Indochina Peninsula (Luo and Lau, 2017, 2018).

2.4. Estimation of urbanization effect and contribution

To determine the urbanization effects on HW, all stations are classified into urban and rural categories using a dynamical classification scheme based on land use change (Liao et al., 2017). A circular buffer with a particular radius of 8 km for each station is first established, then the BAF around a station is calculated as the proportion of artificial surfaces to the total area of the circle (Liao et al., 2017). A greater (smaller) BAF indicates higher (lower) urbanization level around the station. Therefore, the stations with 15% or higher BAF within the buffering circle are classified into urban type, and the others are considered as rural type. BAFs are calculated separately in eight different sub-periods, i.e., 1971–1980, 1981–1990, 1991–1995, 1996–2000, 2001–2005, 2006–2008, 2009–2010, and 2011–2014, according to the data availability.

To quantify the effect of urbanization on HW, the mean HW measures for urban and rural sites are obtained separately to calculate their corresponding trends, denoted as T_u and T_r , respectively. As suggested by Ren and Zhou (2014), the urbanization effect is then defined as the difference between the urban and rural trends: $\Delta T = T_u - T_r$, and the urbanization contribution is defined as the proportion that urbanization effect accounts for the overall trend at urban stations: $C_u = \left| \frac{\Delta T}{T_u} \right| \times 100\%$ (Ren and Zhou, 2014).

2.5. Trend estimation and significance test

The Theil–Sen's estimator (also known as Sen's slope) is employed to detect the possible trends within the HW series (Sen, 1968). This estimator fits a trend line to a time series $x_1, x_2, \dots, x_n$ by selecting the median of the slopes of all lines through all pairs x_i and x_j at the time i and j :

$$\beta = \text{Median} \left[\frac{x_j - x_i}{j - i} \right], \text{ for all } i < j$$

The significance of the trend of a time series is evaluated by the modified Mann-Kendall (mMK) trend test method (Hamed and Rao, 1998). The MK statistics S for a time series is calculated as:

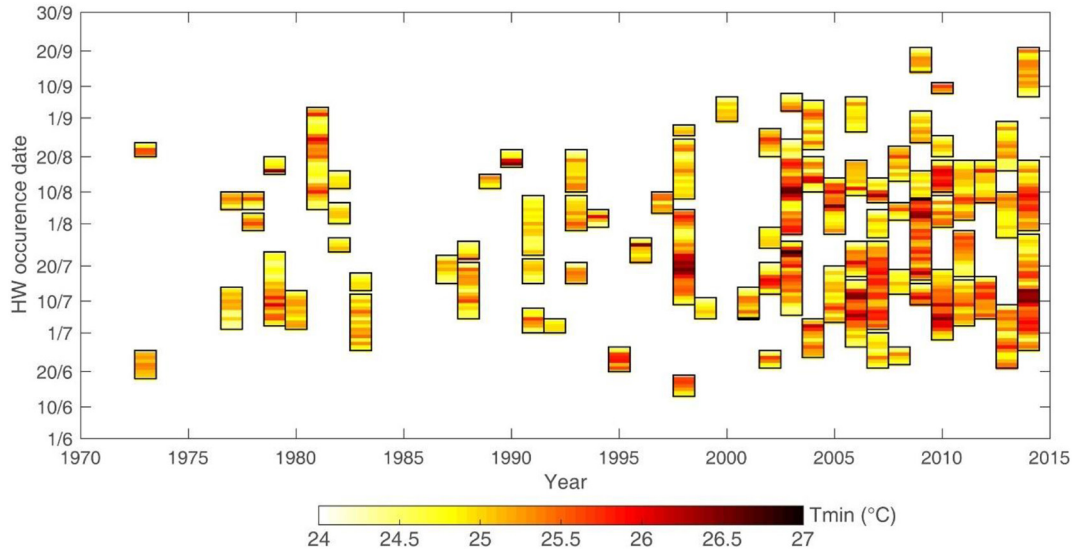


Fig. 4. Occurrences of regional HWs in Fujian during 1971–2014. The horizontal axis denotes year, and the vertical axis denotes the occurrence date of the HW event. Each black box indicates an HW event, and shading indicates the corresponding daily $T_{\min}$ during the event. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

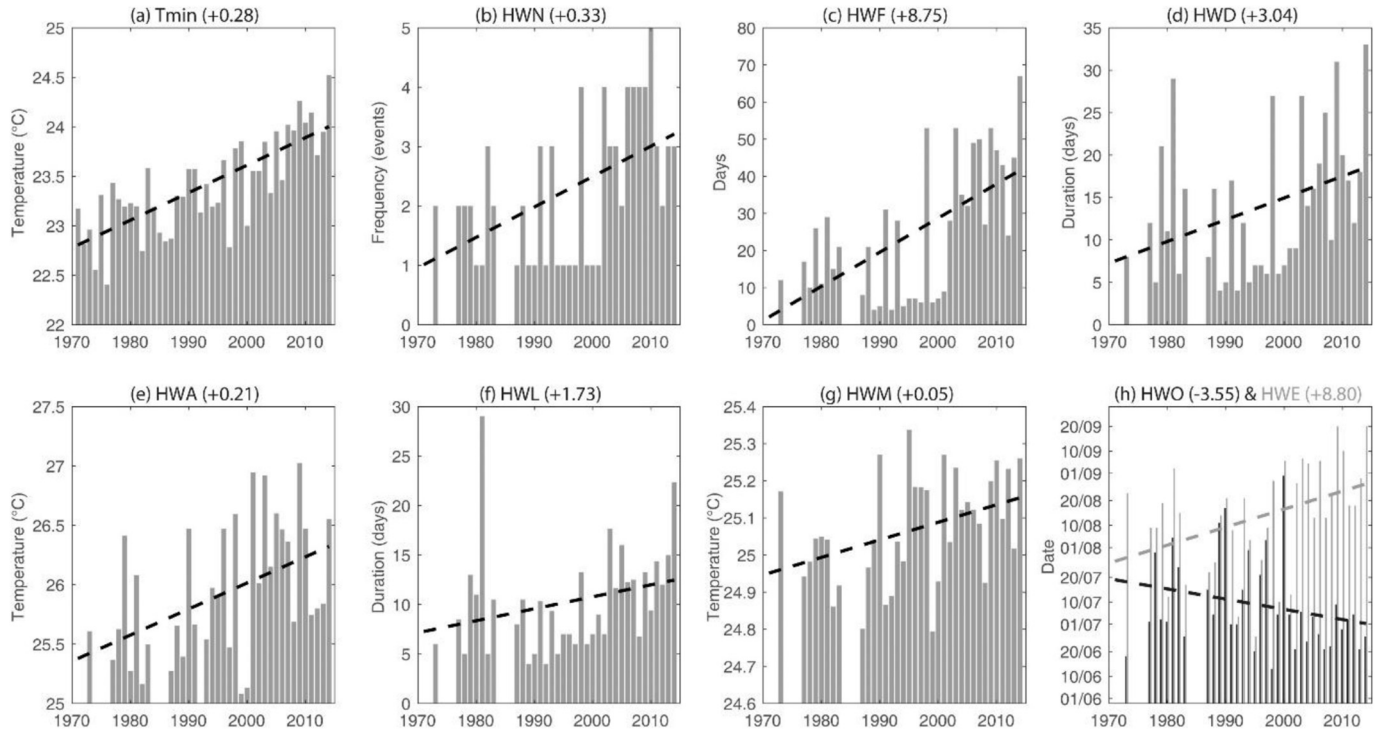


Fig. 5. Time series of (a) seasonal mean $T_{\min}$, (b) HWN, (c) HWF, (d) HWD, (e) HWA, (f) HWL, (g) HWM, (h) HWO (dark strips) and HWE (light strips) for HWs occurring in Fujian during 1971–2014. Straight lines indicate their corresponding linear trends. Numbers in the title denotes the trend in decade⁻¹.

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i), \text{ where } \text{sgn}(x_j - x_i) = \begin{cases} +1, & \text{if } x_j - x_i > 0 \\ 0, & \text{if } x_j - x_i = 0 \\ -1, & \text{if } x_j - x_i < 0. \end{cases}$$

Then, the significance of the trend is obtained by normalizing the test statistic S :

$$Z = \begin{cases} \frac{S-1}{\sqrt{V(S)}}, & \text{if } S > 0 \\ 0, & \text{if } S = 0 \\ \frac{S+1}{\sqrt{V(S)}}, & \text{if } S < 0 \end{cases}$$

where $V(S)$ is the variance of S , as given by $V(S) = n(n-1)(2n+5)/18$. Hamed and Rao (1998) suggested that this estimate of $V(S)$ is biased when autocorrelation exists in the time series. Therefore, they proposed the mMK method that deals with the autocorrelation by changing $V(S)$ to $V^*(S) = V(S) \cdot \text{Cor}$, where Cor is a correction due to the temporal autocorrelation in the data:

$$\text{Cor} = 1 + \frac{2}{n(n-1)(n-2)} \sum_{i=1}^{n-1} (n-1)(n-i-1)(n-i-2)\rho_s(i)$$

where $\rho_s(i)$ is the autocorrelation coefficient at time lag(i). The mMK/MK test and Sen's slope estimator have been widely used to detect the

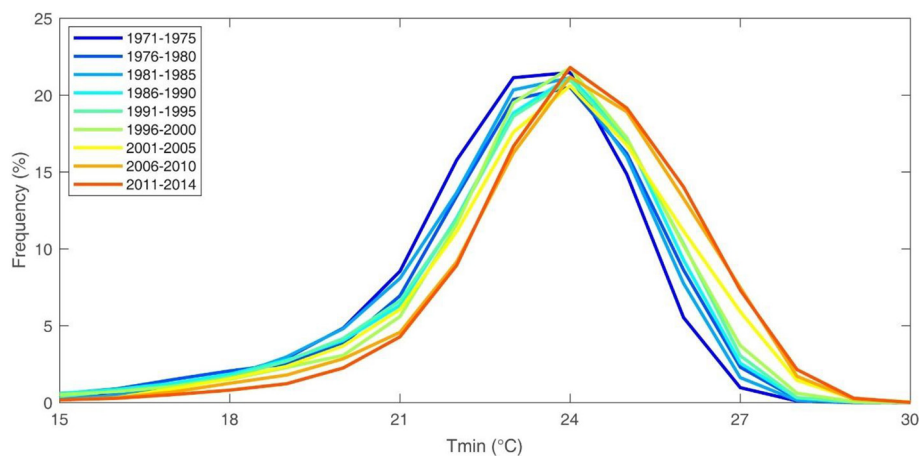


Fig. 6. Frequency distribution of summer daily $T_{\min}$ for every 5-year (4-year for 2011–2014) sub-periods during 1971–2014. Results for various sub-periods are indicated using different colors as depicted by the legend at the top left corner. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

existence of significant trends in climatological and geophysical studies (Andreadis and Lettenmaier, 2006; Zhang et al., 2012; Romanić et al., 2015, 2016; Luo and Lau, 2018; Romanic et al., 2018). More details of these methods can be found in Sen (1968), Hamed and Rao (1998), and Hamed (2008).

3. Results

3.1. Long-term change of regional HW

Based on the spatial average of $T_{\min}$, we identify altogether 82 regional HW events from 1971 to 2014. The occurrences of these HWs in various years are depicted in Fig. 4. It shows that HWs in Fujian are becoming more frequent and severer in the latter part of the study period. It should be noticed that HWs in Fujian are ending later and commencing earlier. HWs mainly occurred in the middle to late July and August in the 1970s, 1980s, and early 1990s, while they become more frequent in June and September after the late 1990s.

Fig. 5 shows the time series of various aspects of HW activities as computed for regional HWs in Fujian. Their long-term trends are summarized in Table 1. All HW metrics exhibit prominently intensifying trends. The regional $T_{\min}$ averaged throughout the summer season shows a warming trend of $0.28\text{ }^{\circ}\text{C decade}^{-1}$ (Fig. 5a). HWN has been increasing significantly by $0.33\text{ events decade}^{-1}$ since 1971 (Fig. 5b). HWF bears a rising trend of $8.75\text{ days decade}^{-1}$ (Fig. 5c). HWD exhibits a prolonging trend of $3.04\text{ days decade}^{-1}$ (Fig. 5d), suggesting that the longest HW of the year is becoming even more persistent. Compared with HWD, HWL has a relatively slighter shortening trend (Fig. 5f). Regarding the HW severity, HWA shows a significantly intensifying trend of $0.21\text{ }^{\circ}\text{C decade}^{-1}$ (Fig. 5e), implying that the HW amplitude tends to be more substantial. Compared with HWA, HWM has a relatively weaker intensifying trend (Fig. 5g), i.e., $0.05\text{ }^{\circ}\text{C decade}^{-1}$.

Besides the duration and severity of HWs, we also examine the trends in the timing of HWs during 1971–2014. Fig. 5h depicts the time series of HWO (i.e., the onset date of the first yearly HW event) and HWE (i.e., the ending date of the last event). HWO exhibits a downward trend of $3.55\text{ days decade}^{-1}$, suggesting that the HWs are commencing earlier; whereas, HWE exhibits a significant upward trend of $8.8\text{ days decade}^{-1}$, indicating that the HWs are terminating later in the calendar year. These results together suggest that the HW season is becoming more broaden.

The secular changes in the HW activities may be illustrated by contrasting probability distribution functions (PDFs) in different epochs. PDFs for daily $T_{\min}$ values in the summer season are presented in Fig. 6. The overall distribution of $T_{\min}$ exhibits a prominent displacement toward the right by $+0.28\text{ }^{\circ}\text{C decade}^{-1}$, while the skewness of the distribution does not have significant long-term trend. These

findings indicate that the intensifying trends in various HW activities are mainly due to the shift of the $T_{\min}$ distribution, rather than its shape. Comparatively, the global mean temperature (over land and ocean) has been increasing by $0.14\text{ to }0.18\text{ }^{\circ}\text{C decade}^{-1}$ during the 1979–2010 period (Grant and Stefan, 2011). The increasing trend of temperature in Fujian goes much faster than that of global temperature, implying that the warming temperature and intensifying HWs in Fujian could be affected by other factors, e.g., Fujian's rapid urbanization (as discussed in the following section).

3.2. Urbanization effect and contribution

The possible effect of urbanization on the changes in various aspects of HW in Fujian is then analyzed. HWs are first identified for each station, and the spatial distributions of the trend of station-based HW measures are examined. These results are demonstrated in Fig. 7. Fig. 7a shows the long-term trends in summer $T_{\min}$ during 1971–2014. It exhibits significant upward trends at most stations (i.e., 64 out of 65 stations), suggesting that HW activities across Fujian are prominently intensifying. Fig. 7b–i presents the trends in various aspects of the HW activity, as computed for 1971–2014. All HW measures, including frequency (HWN and HWF, Fig. 7b–c), duration (HWD and HWL, Fig. 7d & f), amplitude (HWA and HWM, Fig. 7e & g) exhibit intensifying trends in most parts of Fujian. Besides, the onset (HWO, Fig. 7h) and end dates of HW (HWE, Fig. 7i) show advancing and delaying trends, respectively. The advancing HWO and delaying HWE trends collectively imply that the HW season is becoming longer.

Particularly, the intensifying trends in HW show strong spatial heterogeneity. The trends of nearly all HW measures (except for HWN and HWO) are particularly stronger in more densely populated and urbanized areas. For example, the increasing trend in HWF in these regions are more than twice of those in western regions, suggesting that urbanization plays an important role in intensifying HW activities. Both HWD (Fig. 7d) and HWL (Fig. 7f) show prolonging trends in most parts of Fujian. These features suggest that the HW events in these regions are becoming longer-lived. Notably, the prolonging trends in the longest HW of the calendar year (i.e., HWD) are stronger than those in the average HW duration (i.e., HWL). Thus, “extremely” long-lived HWs exhibit more substantially prolonging trends than regular ones. Aside from the frequency and duration of HW, the amplitude of HW show prominently strengthening trends (Fig. 7a & g). More importantly, the trend in HWA is higher than those in HWM, suggesting that severe HW events exhibit more prominently intensifying trend than that of average HW. Regarding the timing of HW, HWO exhibits advancing trends while HWE bears prominently delaying trends in most regions, indicating that HWs are terminating later in the calendar year. We also notice that the decaying trends are more prominent in eastern coastal regions than in western regions. Also, this disparity suggests that

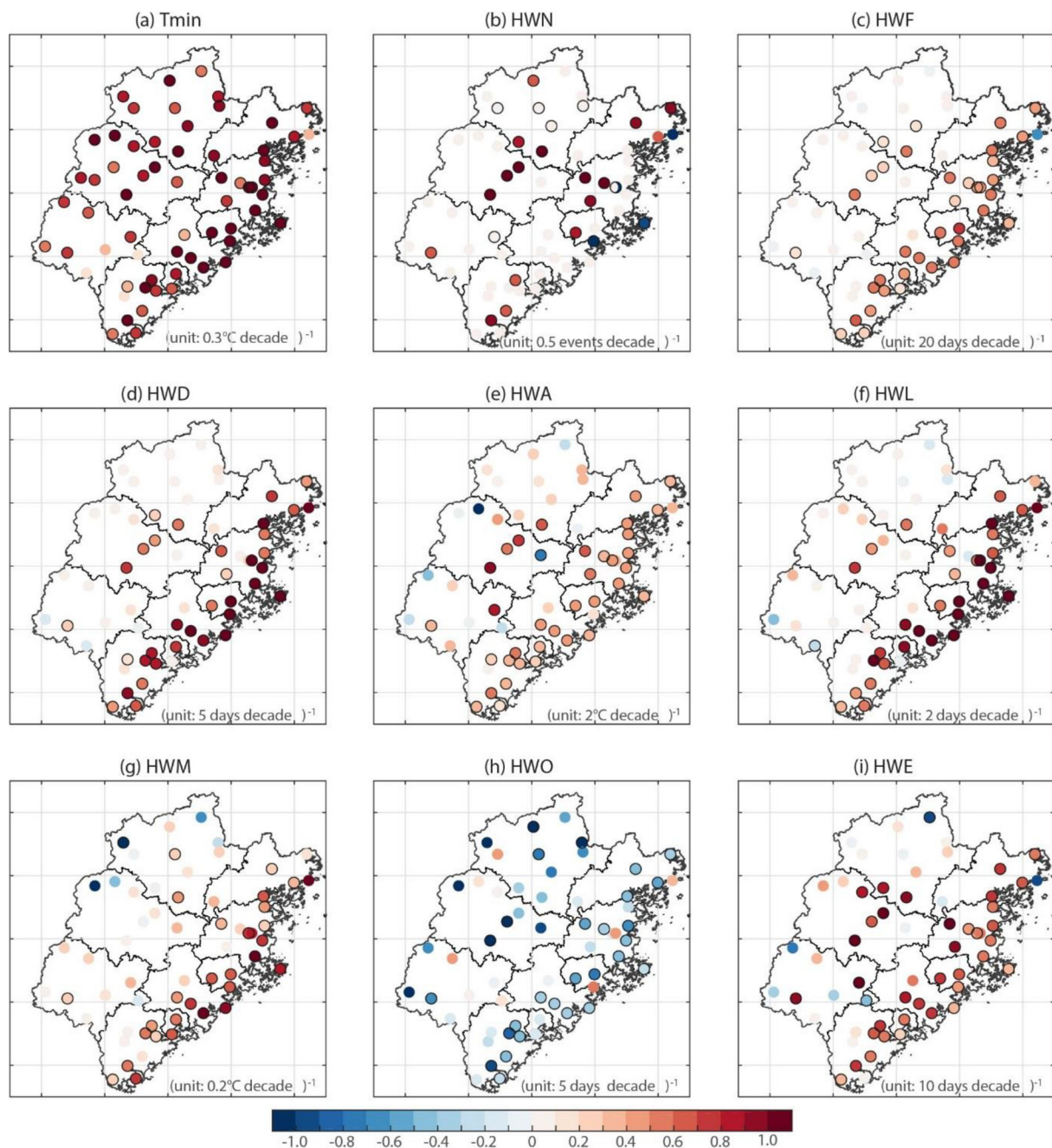


Fig. 7. Spatial distribution of the trends of HW measures during 1971–2014. Black circle denotes the station with the significant trend at the 0.05 level. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

urbanization can additionally intensify the HW activity in Fujian.

The possible effects of urbanization on the HW activity are estimated by comparing different HW trends for urban and rural sites, as classified by a dynamical scheme based on BAF (see Section 2.4). Different combinations of radii and threshold of BAF may generate different classification results. Fig. 8 shows the mean difference between urban and rural stations (i.e., urban-minus-rural) with different combinations of radii and BAF thresholds. It indicates that the combination of 8-km radius and 15% BAF threshold produces the largest urban-minus-rural difference. Therefore, we adopt this criterion to classify all stations into urban and rural types in various sub-periods of 1971–2014. The varying numbers of urban and rural stations in Fujian are shown in Fig. 8b. The number of urban stations significantly grew from three in 1971–1980 to 19 in 2011–2014.

By dynamically classifying urban and rural stations, HW measures

for urban and rural categories in different sub-periods are then generated and compared. Fig. 9 shows their yearly statistics and Table 2 summarizes the estimated urbanization effects and contributions. All HW measures except for HWE at urban stations are larger than those at rural stations, demonstrating that HW measures at urban stations exhibit even more prominently intensifying trends than rural stations.

Particularly, seasonal mean $T_{\min}$ for urban and rural sites exhibit warming trends of $+0.31$ and $+0.20^{\circ}\text{C decade}^{-1}$, respectively (Fig. 9a). The urbanization effect for $T_{\min}$ is $+0.12^{\circ}\text{C decade}^{-1}$, and urbanization contribution reaches 37.2%. Compared with seasonal mean $T_{\min}$, urbanization contributions on HW measures are even stronger. Particularly, the annual frequency (i.e., HWN, Fig. 9b) of urban and rural HW have upward trends of 0.38 and 0.23 events decade^{-1} , respectively. The urbanization effect on (contribution to) the increase in HWN is 0.15 events decade^{-1} (40.3%). As shown in Fig. 9c,

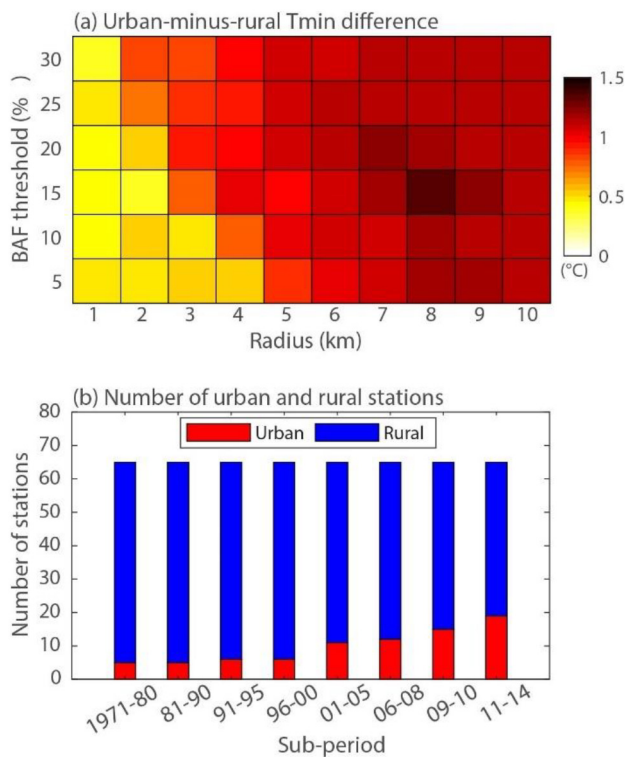


Fig. 8. (a) Urban-minus-rural T_{min} difference using the dynamical classification schemes with various buffering radii and BAF thresholds; (b) numbers of urban and rural sites in different sub-periods based on the classification scheme with the 8-km radius and the 15% BAF threshold. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the increasing trend in HWF at urban sites (i.e., $6.58 \text{ days decade}^{-1}$) is more than twice of that at rural sites (i.e., $2.80 \text{ days decade}^{-1}$). Urbanization contributes to around 57.4% of this increasing trend (i.e., $3.78 \text{ days decade}^{-1}$).

Fig. 9d and f show the times series of the longest (i.e., HWD) and average duration (i.e., HWL) of HWs. HWD at urban and rural sites get prolonging trends of $3.39 (1.96)$ and $1.68 (0.77) \text{ days decade}^{-1}$, respectively. These trends are higher than HWL, showing a more prominent prolonging trend in long-live HW events than short-lived ones. Urbanization effect on HWD (HWL) is $1.71 \text{ days decade}^{-1}$, contributing to 50.4% (60.8%) of its total trend.

HWA in urban and rural areas show intensifying trends of 0.65 and $0.48 \text{ }^{\circ}\text{C decade}^{-1}$, respectively (Fig. 9e). For both types, HWA has much stronger intensifying trend than HWM, i.e., 0.12 and $0.06 \text{ }^{\circ}\text{C decade}^{-1}$ for urban and rural types, respectively (Fig. 9g), indicating that severe HW events bear even more substantial intensifying trend than regular ones. Moreover, the urbanization effect on HWA is stronger than that on HWM as well, by 0.18 and $0.08 \text{ }^{\circ}\text{C decade}^{-1}$, respectively. Urbanization contributes to these two metrics by 27.0% and 65.0% decade^{-1} .

Besides the frequency, duration, and magnitude of HW, the HW timing at urban and rural sites have distinguishable trends. Fig. 9i shows that HWO at urban and rural sites has advancing trends of 1.79 and $0.42 \text{ days decade}^{-1}$, respectively. Urbanization can advance the onset dates of the yearly HW event, and the urbanization effect (contribution) is $-1.37 \text{ days decade}^{-1}$ (76.6%). Nevertheless, HWE has delaying trends of 3.87 and $2.48 \text{ days decade}^{-1}$ for urban and rural stations, respectively. Urbanization can induce an additional delaying trend of $1.39 \text{ days decade}^{-1}$, accounting for 35.8% of the total trend for urban sites.

4. Discussions

The long-term trends of hot extremes and HWs under global warming have attracted much attention in recent decades (Easterling et al., 2000a; Hu et al., 2003; Horton et al., 2016; Lu and Chen, 2016). Besides global warming, HWs can also be exacerbated in urban areas due to the urban heat island (UHI) effect (Landsberg, 1981; Basara et al., 2010; Jason and Christopher, 2015; Mishra et al., 2015; Oleson et al., 2015), i.e., temperature in urban areas is almost always higher than the surrounding regions (Oke, 1973). For example, the warming T_{min} trend in the US is nearly three times greater in urban than rural areas during 1960–1996 (DeGaetano and Allen, 2002). Hausfather et al. (2013) analyzed the U.S. Historical Climatology Network records and estimated that urbanization contributes to 14–21% of the increases in T_{min} since 1895 and 6–9% since 1960. A recent study over 50 US large cities reveals that on average the annual HW frequency increased by 0.6 events per decade during 1961–2010 (Habeeb et al., 2015). These trends are nearly twice of the global warming rate, and UHI is the dominant driver of the warming trend at urban scale (Stone et al., 2012). It is also projected that the frequency of extremely hot nights will increase by 50% by 2050 in large cities globally, these increases are much higher than the surrounding rural areas (McCarthy et al., 2010). HW is suggested to cause higher mortality risk in urban than rural areas (Gabriel and Endlicher, 2011). During HWs, UHI can produce longer, consecutive stressful temperatures, thus posing more significant risks than isolated hot days to human health (Kalkstein et al., 2011; Jason and Christopher, 2015). Therefore, a comprehensive understanding of the urbanization effects is helpful for mitigating extreme heat event and reducing the impacts exerted by these events at the local scale.

The possible effects of urbanization on regional climate change in parts of China have been documented in the literature (Si et al., 2014; Chen and Frauenfeld, 2016; Sun et al., 2016b). However, most of these studies examined the daily extremes, with relatively fewer focusing on consecutive events such as HWs (Zuo et al., 2015; Wang et al., 2017; Yang et al., 2017). Moreover, the studies on China's urbanization effect concentrate in the North China plain (Ren et al., 2008; Si et al., 2014), the Yangtze River delta (Gu et al., 2011; Wang et al., 2017; Yang et al., 2017), and the Pearl River Delta (Luo and Lau, 2017); whereas, no systematic study has been conducted to examine the urbanization effects in Fujian Province, one of the most densely populated and highly urbanized regions in the world. Our study, to the best of our knowledge, is the first attempt to examine the HW changes and urbanization effects in Fujian.

Compared with other parts of China, our results show that the warming trend in Fujian is considerably higher than the national mean (Ren et al., 2005; Ren and Zhou, 2014). Notably, the urbanization effect in Fujian (i.e., $\approx 50\%$) is about twice of the national level, i.e., around 20% as reported by Ren and Zhou (2014). The urbanization effect in Fujian is comparable to those in the Yangtze River Delta, e.g., 56.8% in Hangzhou of Zhejiang Province (Chen et al., 2014), and the Pearl River Delta with approximately 50% urbanization effect (Luo and Lau, 2017). The local or provincial government and related departments should consider these profound urbanization contributions during policy making and resource management, thus better mitigating the increasing risks exerted by warming climate and intensifying extreme events.

Previous studies often used a static scheme to classify urban and rural types with the fixed most recent population or land cover data [e.g., Jin et al., 2015]. Using these static schemes may underestimate the effects of urbanization on surface warming since some urban stations could have been transformed from rural type (see Fig. 8b). Instead, here we use a dynamical classification scheme based on time-varying land use/cover maps in different sub-periods. Compared with the conventional static method, this dynamical approach can realistically capture the urbanization progress, thus potentially reducing the uncertainty in estimating the urbanization effects (Yang et al., 2011; Liao et al., 2017; Yang et al., 2017).

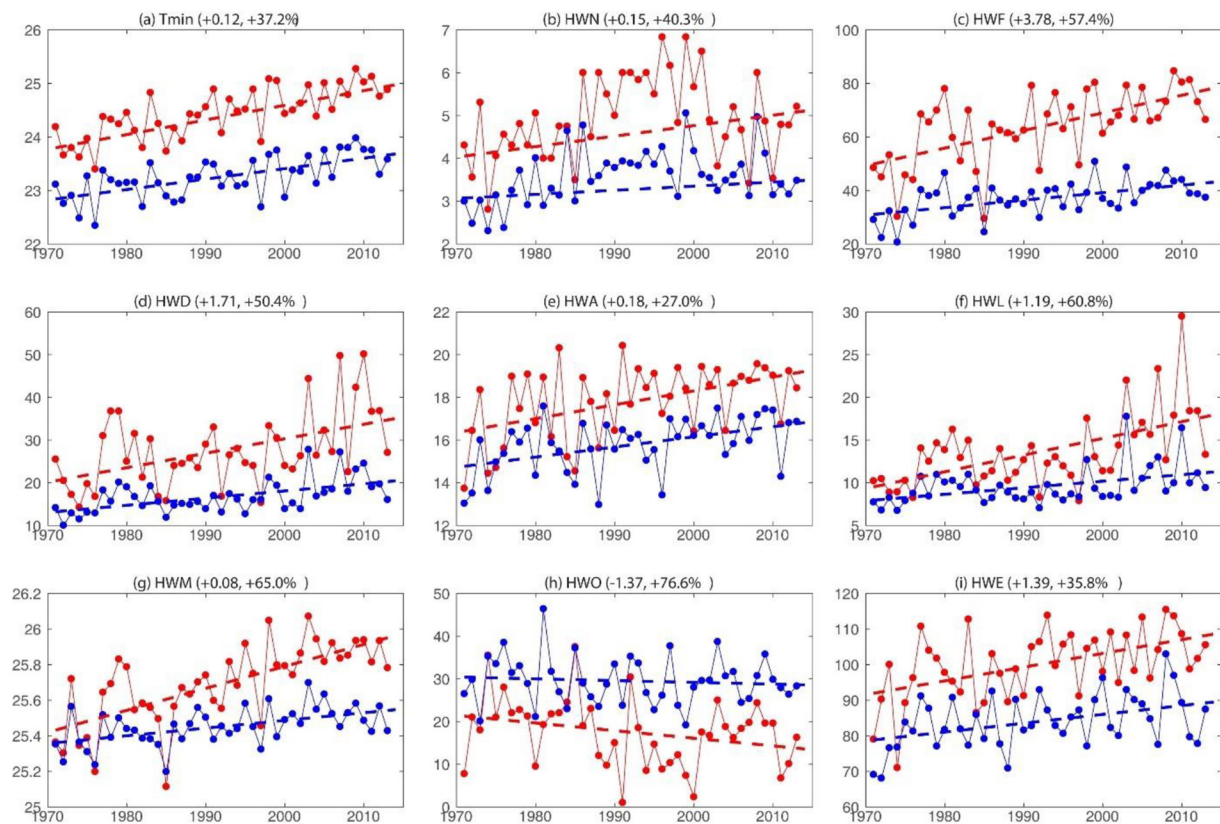


Fig. 9. Time series of (a) seasonal mean $T_{\min}$, (b) HWN, (c) HWF, (d) HWD, (e) HWA, (f) HWL, (g) HWM, (h) HWO, and (i) HWE as calculated for urban (red) and rural (blue) sites in Fujian during 1971–2014. Dashed straight lines indicate their corresponding trends. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Definitions of heat wave (HW) measures and regional HW trends over the period 1971–2014 (unit: decade⁻¹). All trends are significant at the 0.05 level, as obtained by the modified Mann-Kendall trend test (Hamed and Rao, 1998).

HW measures	Definition	Trend
Seasonal $T_{\min}$	Mean $T_{\min}$ averaged throughout the season (°C)	+0.28
HWN	Yearly number of HW events (event)	+0.33
HWF	Yearly sum of participating HW days (day)	+8.75
HWD	Length of the longest yearly event (day)	+3.04
HWA	Hottest day of the hottest yearly event (°C)	+0.21
HWL	Average length of all yearly events (day)	+1.73
HWM	Average magnitude of all yearly events (°C)	+0.05
HWO	Onset date of the first event of the year (day)	−3.55
HWE	Ending date of the last event of the year (day)	+8.80

Table 2
Trends of HW measures for urban and rural sites, and urbanization effect (UE) and contribution (UC) to the HW trends.

HW measures	Urban (decade ⁻¹)	Rural (decade ⁻¹)	UE (decade ⁻¹)	UC (%)
Seasonal $T_{\min}$ (°C)	+0.31	+0.20	+0.12	37.2%
HWN (events)	+0.38	+0.23	+0.15	40.3%
HWF (days)	+6.58	+2.80	+3.78	57.4%
HWD (days)	+3.39	+1.68	+1.71	50.4%
HWA (°C)	+0.65	+0.48	+0.18	27.0%
HWL (days)	+1.96	+0.77	+1.19	60.8%
HWM (°C)	+0.12	+0.04	+0.08	65.0%
HWO (days)	−1.79	−0.42	−1.37	76.6%
HWE (days)	+3.87	+2.48	+1.39	35.8%

It is also noted that many previous studies on consecutive HW event examine only the changes and urbanization effects in its frequency, and the other aspects of this severe extreme event such as its timing (i.e., the onset and ending dates of HW) have yet to be investigated. In this study, we conduct a comprehensive investigation on multi-faceted aspects of the HW activity including frequency, duration, magnitude, and timing (see Table 1). We find that HW in Fujian tends to occur earlier and end later and the local urbanization can remarkably amplify these trends. Meanwhile, we also compare the extremely severe HW events (HWA and HWD) and regular ones (HWL and HWM) and find that severer HWs exhibit stronger intensifying trends than regular events. Urbanization can induce more profound impacts on severer events than regular ones. Through the investigations of various aspects of the HW activity, we give a broader picture of the HW behaviors and urbanization effects than the existing studies. It is, therefore, recommended to include these multi-faceted HW indicators in the studies of climate change and extreme climate events.

5. Conclusion

Understanding the changes in HW is important for formulating mitigation and adaptation measures to cope with the extreme event. Most existing studies on the urbanization effects in China concentrate in the areas of the North China Plain and the Yangtze and Pearl River Deltas and mainly focus on daily temperature extremes. In this study, we go beyond these studies by investigating the changes in multiple aspects of the HW activity (i.e., frequency, duration, magnitude, and timing) in Fujian Province, Southeast China. We find that HWs in Fujian are becoming more frequent, stronger, longer, earlier commencing, and later terminating in the past decades. Particularly, severe (i.e., stronger and longer-lived) HW events have even stronger intensifying trends than regular ones.

Furthermore, the effects of local urbanization on these changes are also quantified by dynamically classifying urban and rural stations based on time-varying land use/cover maps. Compared with the fixed scheme which assumes that no rural stations have been transformed into urban ones, this dynamical method can give a better estimation of the urbanization effect by capturing the dynamical urbanization process. We estimated that the urbanization effect on (contribution to) summer mean $T_{\min}$ is $0.12^{\circ}\text{C decade}^{-1}$ (37.2%). Urbanization contributes to approximately 50% of the total intensifying trends of the HW activity in Fujian, higher than the effect on summer mean $T_{\min}$. It induces an additional increase of 0.15 events (3.78 days) decade^{-1} to HW frequency (participating days). Meanwhile, 50.4% (60.8%) of the prolonging trend in the average (longest) duration and 27.0% (65.0%) of the intensifying trend in the average (strongest) magnitude are attributable to local urbanization. Moreover, we find that urbanization advances (delays) the onset (ending) date of the first (last) yearly HW event by 1.37 (1.39) days decade^{-1} , accounting for 76.6% (35.5%) of the total advancing (delaying) trend.

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